EUDP IEA Task 41
Delivarable 3.1 - Control strategies of wind turbines in future distribution systems

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Content

Summary

This report constitutes part of the work package deliverable 3.1 of the EUDP IEA Task 41 project, funded by Energy Technology Development and Demonstration Program (EUDP) of the Danish Energy Agency. The report presents a brief snapshot of the current research on wind power plant support from weather dependent active distribution networks, research carried out at DTU Wind and Energy systems department. It draws upon the research work carried out by the PhD student Aeishwarya Baviskar, under the supervision of Anca D. Hansen and Kaushik Das.

1. Introduction

This report has been produced with the intention of giving an overview of the challenges and opportunities in future distribution networks with large share of renewable energy sources (RES), such as wind power plants (WPPs) and solar power plants (SPPs). The increased penetration of WPPs in distribution networks challenges the distribution system operators (DSOs) to improve and optimize networks' operation.

The report is providing first an overview of the most relevant challenges of the DSOs for steady-state operation in the distribution network with a large share of RES, namely, sustained over-voltages, voltage fluctuations, increased power losses in the network, growing stress upon the network assets and bi-directional interactions with the upstream grid or transmission system. The report is then describing the development of a novel comprehensive multi-voltage level active distribution network model based on real Danish network data along with load time-series and correlated weather dependent generation time-series, for about a year. The distribution network model embodied with a large share of RES, with generation time-series simulated from meteorological data is an open-source network model. It is entitled as the DTU 7k Bus Active Distribution Network (DTU-ADN) and is accompanied by load time-series aggregated at 60 kV, 10 kV and 0.4 kV. This active distribution network model, flexible to furthermore incorporate other assets such as electric vehicle charging stations, storage, can be used to study, optimize, and control the effects of weather-dependent generation and other network assets in future distribution networks. This report presents some results of the developed control and optimization algorithms for active management of future distribution network, based on the enhanced control capabilities of future network converter connected RES.

1.1 EUDP IEA Task 41: Distributed Wind

This work constitutes part of a work package deliverable 3.1 of the EUDP IEA Task 41 Distributed Wind project. A summary of this project is given here:

The overall objective of this project is to identify and explore studies of Danish interest of Distributed Wind (DW) for cost effective technology development and integration into a continuously evolving energy system. This is done by collaborating and contributing to the IEA Wind TPC Task 41 international activities on DW turbine technology development and assessment in a series of dedicated work packages (WPs). IEA Wind TPC Task 41 is an international network centered on international collaboration and coordination in the field of DW. The purpose is to accelerate the development and deployment of DW technology as one of the leading generation sources in global renewable markets, the facilitation of easier and faster DW integration into electrical grids, increasing thus the competitiveness of wind and accelerating the replacement of fossils fuels. The IEA collaboration is enforced partly by exchange of information, sharing of results, and conducting analyses and explorative studies in the form of reports and publications and partly by implementing a strong cross IEA Wind TPC Tasks collaboration effort.

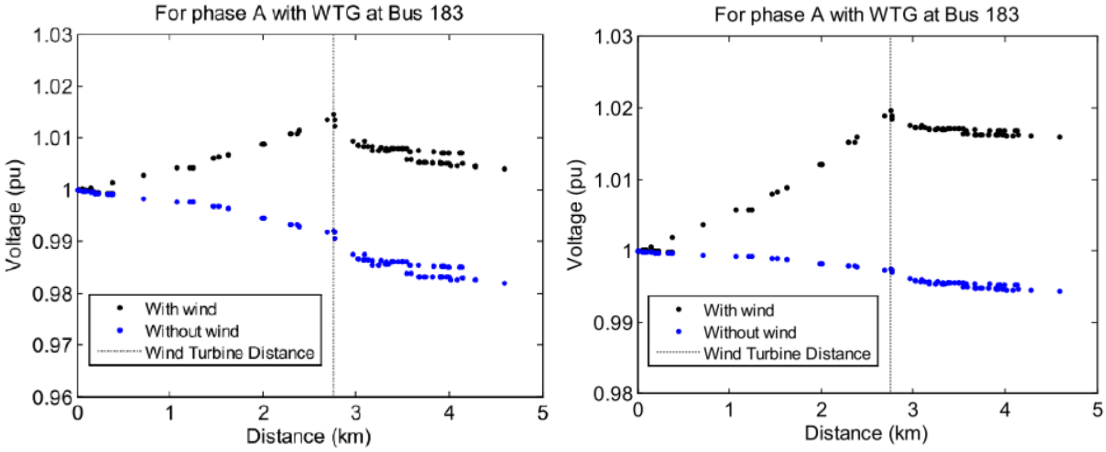
2. Challenges of future distribution systems with large share of RES

As result of the rising in the awareness towards climate change, the increasing share of weather-dependent generation in the distribution networks leads to an enhanced involvement of RES in the electricity grids. Wind power plants (WPPs) and photovoltaic systems (PVs) connected to distribution networks are amongst the most widely deployed weather-dependent distributed generation (DG) sources today. The cumulative installed wind capacity in Europe has reached 205 GW in the year 2019 [1]. As highlighted in [2], in Denmark wind power represents 48% of its electricity mix, followed closely by Ireland with 33%, Portugal 27%, and Germany 26% and the UK with 22%. According to the Danish transmission system operator (TSO) - Energinet, 50% of total energy consumption in Denmark in the year 2019 came from renewable energy of which 47% accounted for wind power plants (WPP) and the rest 3% from solar power [3].

Over the last few years, a large share of wind power and solar PV has also gained momentum in the distribution system [2]. For example, by the end of 2018, 49% of the EU's cumulative photovoltaic (PV) capacity came from rooftop solar (residential 19%, commercial 30%). In Denmark, the introduction of the feed-in-tariff program in the year 2015 saw a surge in the installations of small wind turbines in the distribution system [3]. Germany and the UK had introduced similar feed-in-tariff programs to promote the uptake of small-scale renewable electricity generation in the years 2000 and 2010 respectively. The growing influence of climate change policies and trends in the global uptake of RES will continue in the years to come, emerging future distribution networks to accommodate large share of RES.

The principal challenge behind integrating a large share of RES in the network is that the traditional network was initially designed for unidirectional power flow. Furthermore, the substantially increased amount of RES into distribution networks transforms them into highly weather dependent networks, posing serious challenges to the distribution system operators (DSOs). The additional generation at the distribution level results in a reverse power flow in the network during low load and high generation scenarios, thus being responsible for increased line losses. The variability, uncertainty and non-dispatchable nature of RES might potentially have an adverse impact on network operation and control, challenging the DSOs to deal with additional issues such as like over-voltage, increased power losses and fluctuations, growing overloading of the existing network assets and the interchanging interactions between the distribution network (DN) and transmission network (TN) in the future. Moreover, the current lack of infrastructure for real-time observability, monitoring, and control of roof top PV and small-scale wind installations is an additional challenge for the DSOs. The limited observability of RES in the distribution network adds on to the existing uncertainties in the network due to a high share of weather dependent generation. It becomes thus imperative to actively incorporate control capabilities of RES to aid and improve the operation of distribution grids.

Various studies, conducted and presented in [2] investigate several voltage stability aspects for different load scenarios. Figure 1 shows that the voltage profiles in the network increase whenever a wind turbine is connected to a feeder. Figure 1a shows the increased voltage profiles in the network during full load scenario due to the presence of wind turbines, the maximum voltage being however below 1.02 pu. Figure 1b depicts the simulation results for a 33% full load scenario, and how the voltage profile increases at an even higher voltage level, closer to 1.02 pu.



a) Full load scenario **b) 33% of full load scenario**

Figure 1: Voltage along the feeder with 3MW wind turbine connected - in different load scenarios [2].

The study in [2] also underlines that, the voltage rises due to connecting WTs depends on the equivalent impedance between the reference bus and WT connection point.

Furthermore, as explained in [2], high amount of wind power production in distribution networks can also lead to an increased reverse power flow into the system. For example, Figure 2 shows how the active power exchange with transmission system operator (TSO) can be impacted by an increased wind power production. Notice that the power flow from TSO to DSO is completely reversed when the wind power production is more than 15MW.

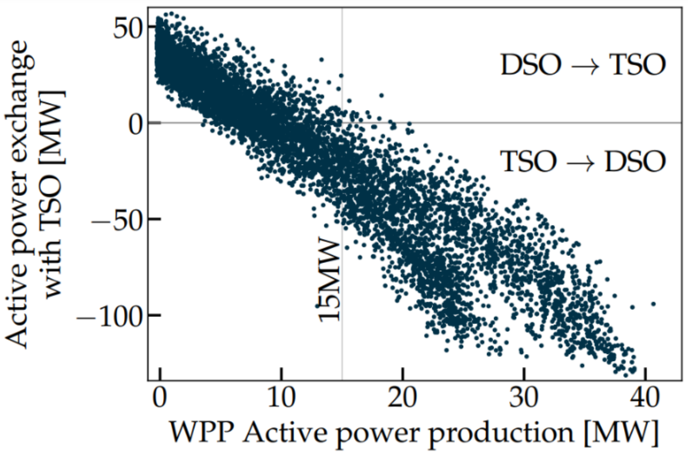


Figure 2 : WPP active power production vs. active power flow from the transmission network [2].

One of the main challenges behind integrating a large share of RES such as WPPs in distribution grids is the increase in active power losses with wind power production. There is a strong positive co-relation between the wind power generation and network losses. This aspect, that high wind power generation in the network, as dominant contributor to reverse power flow, increases the active power loss, is also depicted in Figure 2. plots the power losses against the WPP active power production (reverse power flow). Notice that the region of WPP active power production larger than 15MW revealed in Figure 2 accounts for only 40% of the total time simulated but contributes with 89% to the total losses in the network.

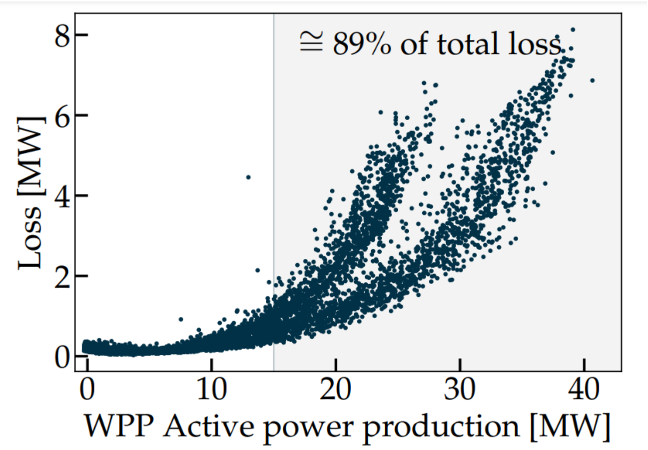


Figure 3: WPP active power production vs. distribution network losses [2].

Figure 4 illustrates the reactive power exchange between the transmission and distribution networks for a Danish distribution network [2]. The convention of power flow in this figure is positive from TSO to DSO. Notice that the distribution network becomes highly inductive, transferring reactive power to the transmission system, as WPPs generate more active power. Remark that in this figure 80% of the total active power losses in the network occur when TSO is supplying reactive power to the DSO. These results underline that it is of high relevance to utilize the local reactive power generation capabilities of WPPs to reduce network losses.

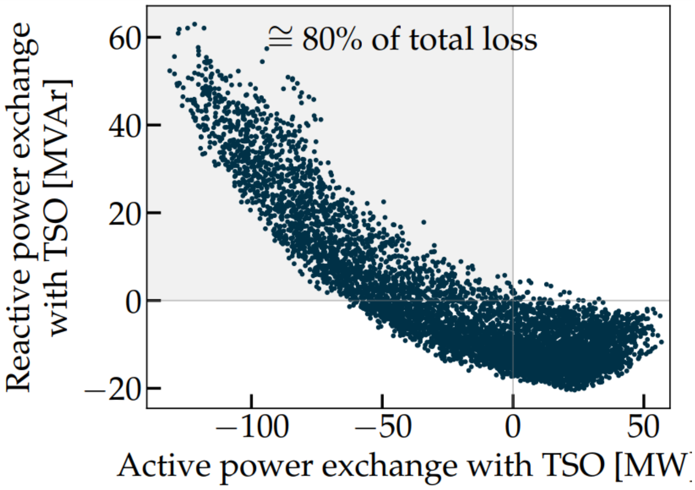


Figure 4: Active power flow vs. reactive power flow from TSO/DSO.

In [4], an optimization methodology to minimize the losses in distribution networks with large share of wind power, exploiting wind power plants capability to control reactive power in coordination with the on-load tap changers (OLTCs) from the MV/HV transformer, is proposed and analyzed. The study, conducted based on measurements from a real Danish distribution network data with a large share of controllable wind power plants (WPPs) under varying wind and load conditions, shows that the reactive power control capabilities of WPPs alone can contribute significantly to loss reduction in distribution networks.

3. Modelling of distribution network with large share of renewable energy sources

Future distribution networks resemble active networks with multiple assets such as RES, combined heat cycle plants, electric vehicle charging, etc. There is, therefore, a growing concern among DSOs for loss of revenue, increased operation cost, and the threat of instability. As the assets in such networks are typically controlled in different voltage levels, the change in power flows not only impact each specific voltage level but also other voltage levels too in terms of voltage profile, power losses, reactive power flow, etc. This has a further impact on the active and reactive power flow to the transmission network.

These aspects have raised the need of detailed studies, analyses, and developed active management techniques for the growing number of beneficial network assets connected in the distribution grid. As a result, the design of benchmark distribution network models has been of interest for much research works. A summary of some network models is presented in [5]. Amongst all the distribution network models presented so far, only few of them include the low voltage levels [6], [7] and only [6] is accompanied with load time-series data for over a year. However, to study the effect of weather-dependent generation in a future active distribution grid, it is crucial to also study the correlation between the load demand and weather-dependent generation at different voltage levels in the network. [5] presents a comprehensive multi-voltage level active distribution network model based on real network data along with load time-series and correlated weather dependent generation time-series, for about a year. The network topology is modelled based on geographical data for various rural, semi-urban, and urban locations. The distribution network is embodied with a large share of renewable generation sources, with generation time-series simulated from meteorological data. The network is also flexible to incorporate other assets such as electric vehicle charging stations, storage, etc. The presented active distribution network model can be used to study, optimize, and control the effects of weather-dependent generation and other network assets in the distribution grid.

The proposed distribution network model in [5], is an open-source network model, entitled as the DTU 7k Bus Active Distribution Network (DTU-ADN), and it is accompanied by load time-series aggregated at 60 kV, 10 kV and 0.4 kV. The distribution network model is developed for control and optimization algorithms for active management of future distribution network. It is using a top-down approach, premised on the 60 kV distribution network model and correlations between load demand and wind and/or solar generation in a low voltage distribution network. This model is also expanded to include 14 10 kV-0.4 kV networks at different 60 kV-10 kV substation nodes. The network topology for the DTU-ADN is generated from geographical data and represents real distribution networks.

The developed benchmark distribution network model described in [5] has a novel strength of high relevance for development of control strategies of different assets for optimal operation of distribution network, while incorporating uncertainty from weather dependent generation and loads:

- Weather-dependent generation time-series simulated from meteorological data and correlated load time-series, derived from measurement data at three different voltage levels.
- Capability to co-simulate a multi-voltage distribution network with large share of RES at different voltage levels to evaluate impact of distributed generation on the operational conditions of a distribution network.
- 18 different realistic and diverse network topologies of 10 kV-0.4 kV networks with different characteristic loads, such as agricultural, household, and/or industrial, and distributed RES.
- Flexibility to incorporate additional network assets such as combined heat and power plants, storage units, electric vehicle charging stations, etc. to investigate performance of active distribution networks.
- Comprehensive platform for development of coordinated control between different assets for optimal operation of distribution network, while incorporating uncertainty from weather dependent generation and loads.

3.1 DTU 7k Bus Active Distribution Network (DTU-ADN)

The DTU 7k-Bus Active Distribution Network (DTU-ADN) [5] is a balanced three-phase multi-voltage network with a high share of weather-dependent renewable energy generation. It spans across three voltage levels, 60 kV-10 kV-0.4 kV, while being connected to the transmission grid via step-up 60 kV/150 kV transformers. The medium voltage (MV) 60 kV network can be connected to 17 distinct 10 kV-0.4 kV networks, simultaneously or in combinations, at different 60 kV-10 kV substations, to form a three-voltage level network.

3.1.1 60 kV Network

The topology of the 60 kV network originates from a real Danish grid. It hosts 25 buses out of which 23 buses connect 60 kV/10 kV substations, and one bus connects to the transmission grid via 60 kV-150 kV step-up transformers. Onload tap changers are present at the 60 kV-150 kV transformer and at the 60 kV-10 kV substation transformers. The 60 kV network hosts three WPPs with installed capacities of 12MW, 15MW, and 15MW, respectively, composed of Type IV controllable wind turbines. Figure 5 illustrates the network topology with its key elements.

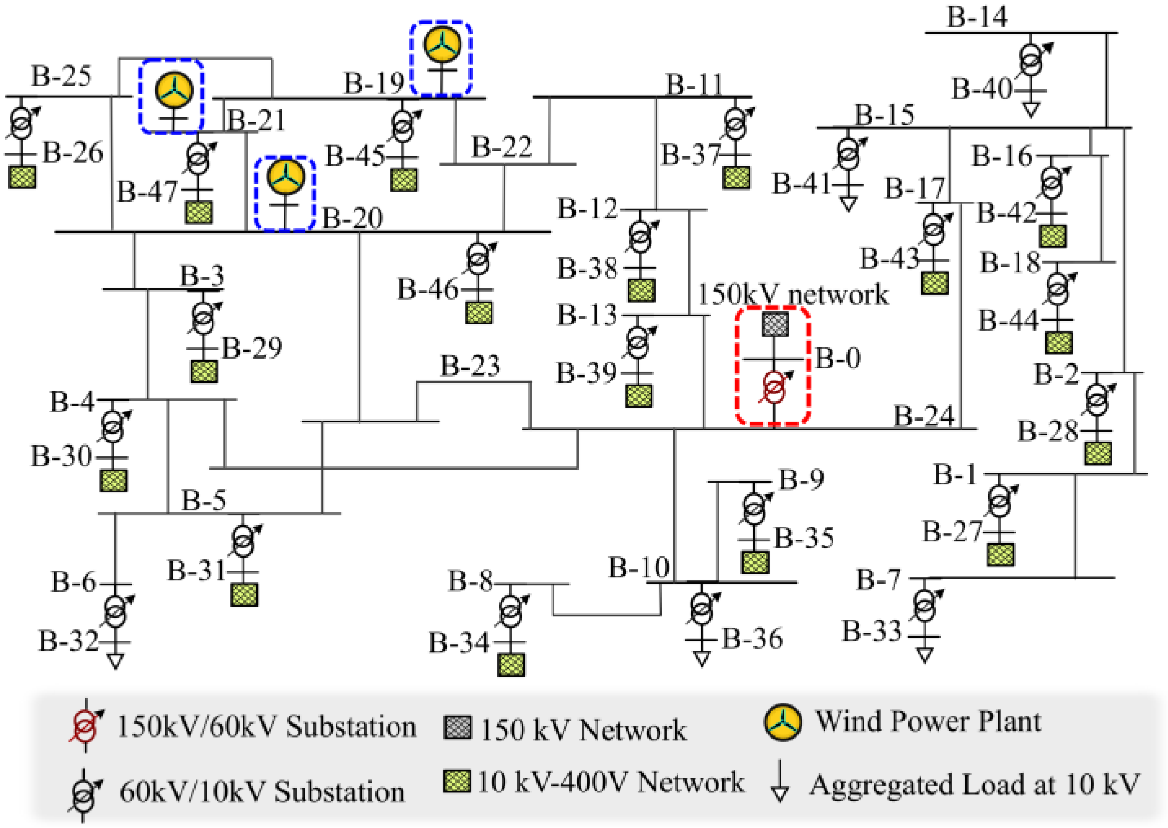


Figure 5: Network topology for the 60 kV network in the DTU 7k-Bus Active Distribution Network indicating locations of the WPPs and 10kV-0.4kV networks.

As described in [5], the measurement data in a real distribution network, based on historical data for 1 year, forms the basis of the load (active and reactive power) and generation time series accompanying the 60 kV grid. Aggregated load time series at all the 60 kV/10 kV substations, and generation time series for the three WPPs are provided for the 60 kV network. Because of a large share of distributed generation, negative values, or reverse power flow is also observed in the aggregated load time series at the 60 kV-150 kV and 60 kV/10 kV substations.

3.1.2 10 kV-0.4 kV Networks

Topology for the 10 kV-0.4 kV networks associated with the DTU-ADN represents unique layouts as they are derived from publicly available data from open street maps [8] using Distribution Network Models module (DiNeMo) [9]. The networks cover varied geographical areas, thus making some networks dense, akin to urban networks, and others more sparse, comparable to rural networks. The number of supply or generation nodes in the networks falls in the range of 40 to 650 nodes. Cumulatively, the entire DTU-ADN consists of approximately 6541 nodes at 0.4 kV, 427 nodes at 10 kV, and 25 nodes at 60 kV which accounts for its name DTU 7k- Bus Active Distribution Network. In addition, there are a total of 291 10 kV/0.4 kV substations with off-load tap changing transformers within the 10 kV-0.4 kV networks.

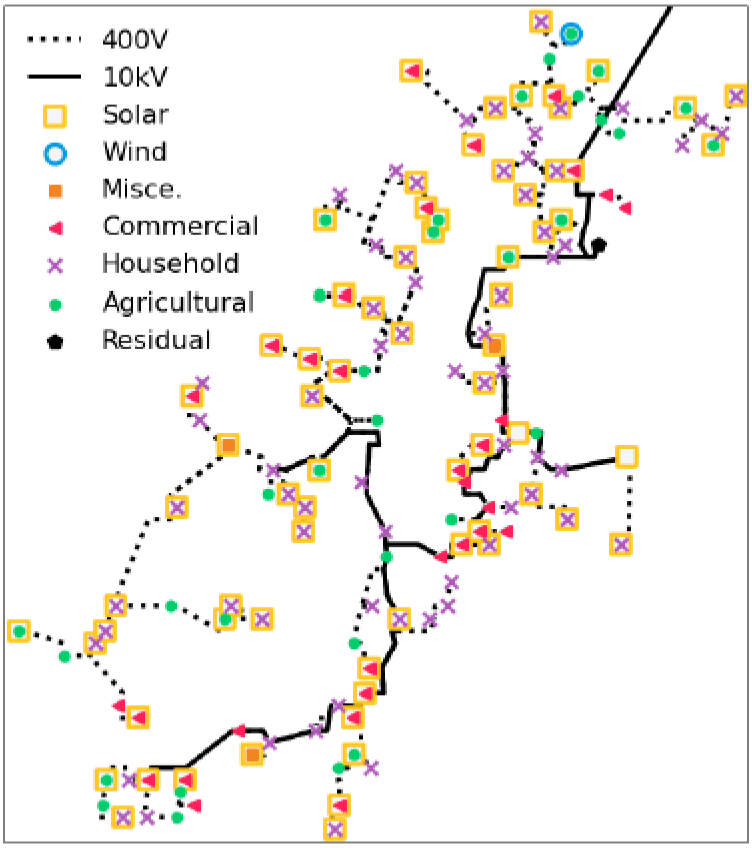


Figure 6: The 10 kV-400V network at Bus 27 illustrating 10 kV and 0.4 kV distribution lines, type of load profiles at each node, location of solar and wind power installations [7]

The DTU-ADN dataset also specifies unique load profiles for each of the 10 kV-0.4 kV nodes. Since, the DTU-AND is a balanced three-phase distribution network model, the 10 kV, and 0.4 kV nodes serve multiple customers connected to these nodes, thus the load and generation time series mirror aggregated values. The load time series provided with the dataset are categorized into four main categories, namely household, industrial including commercial, agricultural, and miscellaneous loads. In total there are 27 different load time series derived from [10]. All the 10 kV-0.4 kV networks have varied proportions of load profiles from each category. Measurement data is used to derive the aggregated load time-series at 60 kV nodes. The load profiles assigned to 10 kV and 0.4 kV nodes represent commercial/industrial, agricultural, household, and miscellaneous loads. Thus, the 10 kV-0.4 kV networks can be further classified in terms of their cumulative maximum load demand from each category into predominantly residential networks, highly industrialized networks, or agricultural networks. Figure 6 shows an example of one of the 10 kV-0.4 kV networks at Bus 27, indicating the network topology, with the distribution lines, and all the nodes with specified load profile category.

3.1.3 Weather-Dependent Generation

Numerous nodes in the 10 kV-0.4 kV networks have either solar or wind or both generation sources installed along with the load. The assortment of installed solar capacities is from a minimum of a few kWs to approximately 2.5MW. Similarly, installed wind capacities range from a minimum of 300kW to a maximum of 16MW. The cumulative installed solar and wind capacities in the DTU-ADN are approximately 26MW and 150MW respectively. There are approximately 1900 distributed generators across the 10 kV-0.4 kV networks, amongst which about 300 installations across 17 networks can actively participate in the grid operations via advanced power electronics control. The distinction between passive and actively participating distributed generation is made according to the Danish grid codes and may vary depending on the local grid codes. The presence of smaller distributed generation units (< 11kW) along with the controllable units account for their different effects on distribution grid operations due to their uncontrollable and controllable properties. Finally, meteorological data is used to simulate wind and solar generation time-series using CorRES [11].

The DTU-ADN model described in [5] provides an opportunity to study multi-voltage distribution networks with distinct characteristics and RES penetration levels. On one hand, the distribution networks can be employed to study, control, and optimize voltage profiles, line losses, network asset operation with high-RES penetration. While on the other hand, such multi-voltage model can be used to promote active participation of distribution networks in the provision of flexibility services, through controllable power electronics-based distributed generation. The DTU-ADN also provides the adaptability to incorporate additional assets such as storage, electric vehicle charging, or analyze demand response in the distribution network. More details about the network modelling methodology and the optimization routine to assign load-generation profiles can be found in [5].

4. Control opportunities of wind power to alleviate distribution network challenges

The increased penetration of RES in distribution networks, because of rising awareness towards climate change, and their involvement in the electricity grid, presents new challenges for the distribution system operators to improve their networks' operation by effectively utilizing the available resources. For example, due to the current widely available low-cost power electronics, wind power plants (WPPs) are a prevalent choice among different options of weather-dependent distributed generation sources to support the network, especially when the benefits for the DSOs are not only technical but also economical [4].

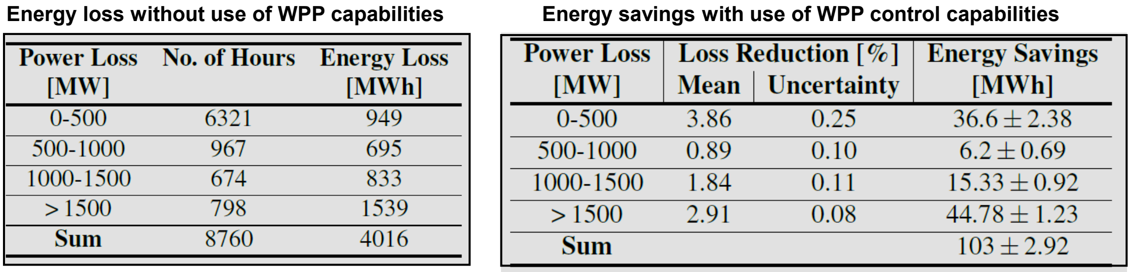
According to the European grid codes [12-14] the RES are required to share some of the duties carried out today by the conventional power plants, such as providing support to the grid in terms of active power control, reactive power supply, maintaining power quality, fault-ride through capability and protection. The main role for such technical requirements is played today by the power electronics existing inside RES. At the distribution level, integration of WPPs offers several benefits, like reducing congestion and power losses in the transmission lines, active support in terms of voltage stability, improved load shedding, as discussed in [15].

Despite the development in WPPs' control capabilities over the last decade due to the presence of power electronics, there is still a gap in the effective use of the WPPs capabilities in distribution networks. For example, the additional electricity production from wind turbines has an impact on the network losses that may change the reactive power flow and thus the variation of the voltage profile throughout the distribution feeders [2]. Especially, the increase of distribution system losses due to wind turbines production has become a greater concern in any power system [16-19]. In [20], it is shown that power losses in distribution networks with high-RES penetration, can increase up to 200 %. Another example where converter connected renewable generators, such as WPPs, can support the network, is in respect to reactive power support needed in distribution grids and voltage regulation support to the transmission network via altering the reactive power feed-in [16]. Over the last years, network operators have been increasingly concerned with procuring reactive power sources as more synchronous generators are planned to be decommissioned and number of distributed generations is on the rise. Reactive power is necessary in the evolving grid with distributed generation to support the additional power flow and avoid expensive grid reinforcements.

4.1 Minimize distribution network losses using wind power

A higher amount of distributed generation also directly translates to more power losses in the network. In this regard, WPPs' capabilities can prove valuable to avoid network congestion, maintain supply and reduce network losses. The work presented in [4] successfully demonstrates that the control capability of WPPs can support distribution system operators by reducing losses in distribution networks. This is done by optimizing the reactive power flow through the distribution networks by controlling reactive power set-points of wind power plants using genetic-algorithm based optimization. The study is conducted on a real Danish distribution network, with a large share of controllable wind power plants, under varying wind and load conditions using actual measurements.

The results in [4] show that WPPs can actively participate in distribution grids to reduce the power losses, by locally supplying / absorbing reactive power. In addition to WPPs, other agents such as tap-changing transformers, capacitor banks etc. can also be controlled, along with WPPs, to further reinforce energy savings. As shown in Figure 7**,** the considered distribution grid has power losses in the range of 0-500MW for approximatively 72% of the total time, when WPPs are not used actively to reduce the losses. However, their contribution to the total energy loss is <25 %.



Energy loss without use of WPP capabilities

Power Loss [MW]	No. of Hours	Energy Loss [MWh]
0-500	6321	949
500-1000	967	695
1000-1500	674	833
>1500	798	1539
Sum	8760	4016

Energy savings with use of WPP control capabilities

Power Loss [MW]	Loss Reduction [%] Mean	Loss Reduction [%] Uncertainty	Energy Savings [MWh]
0-500	3.86	0.25	36.6 ± 2.38
500-1000	0.89	0.10	6.2 ± 0.69
1000-1500	1.84	0.11	15.33 ± 0.92
>1500	2.91	0.08	44.78 ± 1.23
Sum			103 ± 2.92

Figure 7: Impact of WPP control capabilities on energy savings [4].

Figure 7 also shows the results when the optimization method is used to minimize the losses in distribution network, by utilizing WPP control capabilities. The mean and uncertainty in loss reductions along with the energy savings for all bins are shown. The energy savings are calculated by taking a difference between the network losses without using WPP capabilities and network losses when WPP capabilities are used. The uncertainties for the loss reduction for all bins are assumed independent of each other. Notice that uncertainty in loss reduction is high for low values of 'loss before optimization, low for high values of 'loss before optimization' and it depends on the loss in the network without using WPPs capabilities. It should be noticed that by using the proposed optimization methodology, a total energy saving of 103 _ 2.92 MWh is achieved for 1 year based on the representative data.

A suggestion for future work can be to quantify the impact of altering distribution grids' reactive power demand on the TSO/DSO interface. Thus, a holistic optimization can be developed for MV and LV network considering additional assets like PV, tap-changers, other DGs.

4.2 Reactive power support from wind power plants

Centralized synchronous generators have normally been the main source of reactive power supply in the power system along with capacitor banks and VAR compensators at local substations. The power system however is moving towards a decentralized generation structure with decommissioning of larger synchronous generators and large share of modern distributed generators which are connected to the grid with power electronic converters capable of providing reactive power support, such as WPPs.

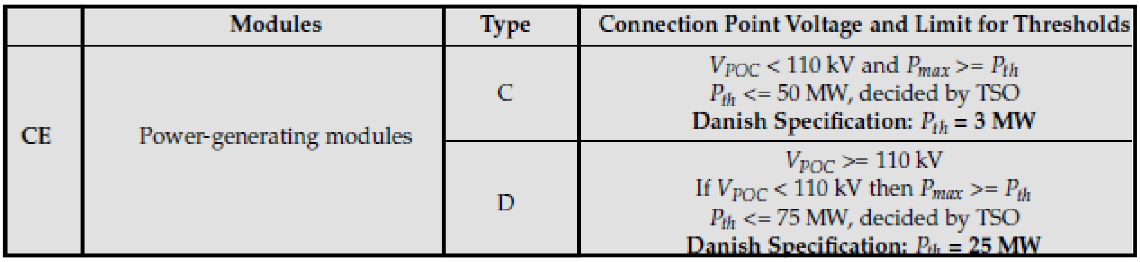
Utilizing the reactive power capability of converter-connected RES, such as WPPs, not only reinforces the capability of the existing distribution grid for additional active power flow but also provides the transmission network with required ancillary services for voltage regulation. Converter-connected RES are an accessible local reactive power source for distribution system operators to optimize network operations, having advanced control capabilities which can be utilized to support DSOs. The converters connecting the RES to the grid generally operate below their maximum rated power depending on resource availability. Thus, the converters can be used as a flexible local reactive power source in the distribution network. However, the non-linearity and non-convexity in the converter equations make their modelling very challenging, which further results in under-utilization of the reactive power capability from these sources [16].

The results in [12] and [16] indicate the potential maximum benefits for a multi-voltage distribution network in terms of reduction in active power loss, voltage profile improvement, and reduced dependence on the transmission network for reactive power supply. In [12] a semidefinite programming based optimal power flow is implemented to find the maximum reactive power support from converter connected generation having two different objectives, namely loss minimization in the distribution network and following a reactive power reference from the transmission network. In [16], the advantages of employing complete converter capabilities for optimal operation of the distribution network are studied via simulations on a real distribution network dataset. The results show both a substantial decrease in the energy losses, an improvement of the voltage profile in the distribution network with high renewable power as well as that the reactive power dependency on the transmission network is reduced.

4.2.1 Grid codes for reactive power for renewable generation units

European grid codes (EU CR) have adapted over time recognizing the control capabilities of converter-connected RES. Danish grid codes, for example, require RES to be able to provide certain reactive power capability depending on their own installed capacity [13], [21]. Nevertheless, the big potential of converter-connected RES to provide reactive power remains under-utilized in the grid codes as they restrict the reactive power within a proportion of the total power rating or with a pre-defined power factor [22-26].

In the EU CR [13], the power-generating units are categorized into four types (i.e. Type A, B, C, D) according to their connection point as well as their installed capacity, regardless of their source of energy, such as wind/solar. Figure 8 depicts the European and the Danish specifications for large converted connected power-generating modules, i.e., Type C and D.



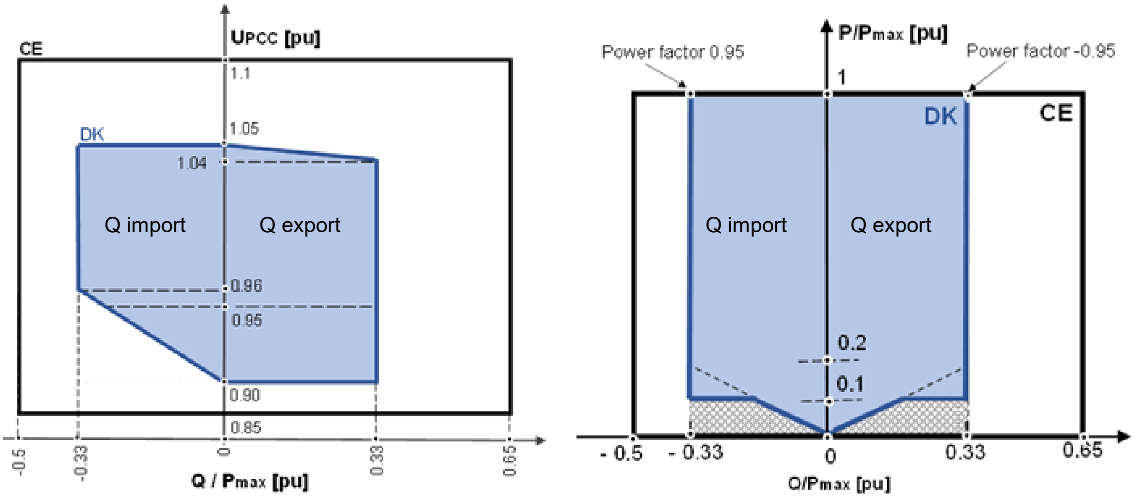
	Modules	Type	Connection Point Voltage and Limit for Thresholds
CE	Power-generating modules	C	$V_{POC} < 110$ kV and $P_{max} >= P_{th}$ $P_{th} <= 50$ MW, decided by TSO **Danish Specification: $P_{th} = 3$ MW**
		D	$V_{POC} >= 110$ kV If $V_{POC} < 110$ kV then $P_{max} >= P_{th}$ $P_{th} <= 75$ MW, decided by TSO **Danish Specification: $P_{th} = 25$ MW**

Figure 8: Danish and European specifications for large converted connected power-generating modules [14].

Notice that, for Type C, the maximum capacity threshold in continental Europe is 50MW, while in Denmark is 3MW. Whereas, for Type D, the maximum capacity threshold in continental Europe is 75MW, while in Denmark is 25MW. The minimum required services from the power-generating modules depend on their category. For example, Type D units are expected to provide a wide range of services in relation to voltage stability, fault ride through capability, frequency services etc. owing to their installed capacity and advanced converter capabilities.

Furthermore, the EU grid code requirements [13] emphasize that, whenever generating active power, the RES also should have reactive power control capability, contributing thus to the power system voltage stability. The reactive power capability is depending on the type of power-generating unit and is crucial for controlling the voltage locally across an electricity grid, typically in response to power system voltage variations. Reactive power requirements are usually specified using U-Q/Pmax profiles and P-Q/Pmax profiles [13]. Both profiles are for reactive power flow at connection points and define the boundaries in which the power plant shall be capable of providing reactive power. A power generating unit must be capable of supplying reactive power both when it is operating at maximum capacity as well as below its maximum capacity. The U-Q/Pmax profile shows the requirements for reactive power capability at maximum active power capacity at different voltage levels, while P- Q/Pmax profile specifies the requirements for reactive power capability at different active power levels below maximum capacity.

Figure 9 depicts the shapes and values for U-Q/Pmax and P- Q/Pmax profile for Type D power-generating units - indicated by the blue profile areas for Denmark [24], and outer black envelop for EU [13]. Notices that the EU commission regulation fixes the range but hands the flexibility for service requirements on the relevant system operators or the national transmission system operators, leaving thus each individual TSO to define its own reactive power requirements through an inner envelope.



(a) at maximum capacity

(b) below maximum capacity

Figure 9: Reactive power provision capability requirements for power generating units in Denmark (DK), within the recommended envelope by EU CR for Continental Europe (CE) [14].

Power generating units must be designed such that the operating point for the delivery of reactive power can lie anywhere within the specified inner envelop. The inner envelope (depicted by the blue lines) can take on different shapes that vary from area to area, but it should always be positioned within the limits of the fixed outer envelope specified by the EU CR. The grey shaded region in the P-Q/Pmax profile denotes the area where the reactive power capability is allowed to be limited by a reduced number of operating units, due to startup and shutdown as a function of primary energy, maintenance or failure. The reactive power capability of Type D generating units is for example analyzed in [28] and illustrated in Figure 10.

The work described in [16] analyzes in details both the effect of reactive power on the active power losses in the multi-voltage level DN, the ability of a DN with large share of RES to provide reactive power flexibility for the transmission network as well as the impact of reactive power of capability of converter-connected RES on the voltage profiles.

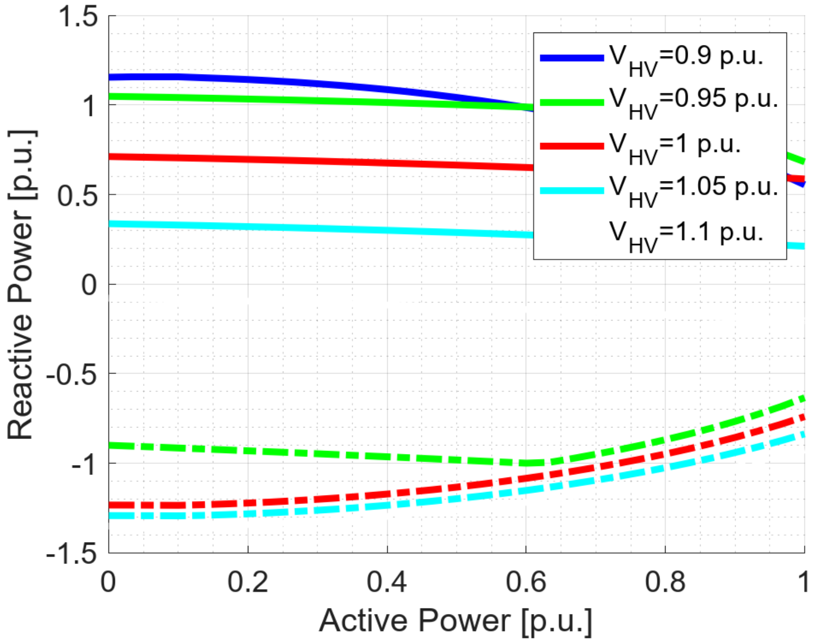


Figure 10: Reactive power capability curve for a Type D unit for different voltages levels on the HV side [28].

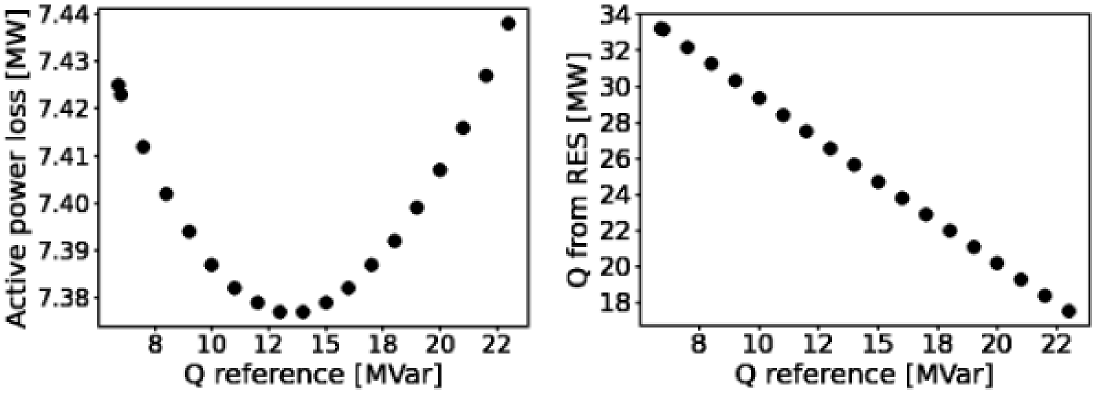
4.2.2 Active power loss minimization

The results presented in [16] regarding active power loss minimization show that the total loss reduction due to local reactive power from RES depends upon multiple factors, including the load demand, generation and the location of the demand and generation relative to each other. It should be highlighted that the amount of generation from the RES directly has an impact on their reactive power contribution due to physical constraints of the grid side converters. One of the constraints is the total apparent power rating of the grid side converter which limits the reactive power at very high generation levels. The other constraint is to reduce the loss within the converter system if it acts as a reactive power source at very low generation levels.

4.2.3 Reactive power at the transmission-distribution interface

Regarding the reactive power transfer between transmission and distribution network, the results in [16] demonstrate the potential of a DN with large share of RES to provide reactive power services to the transmission network. The optimal power flow, formulated in such a way to allow the DN to act as a source or sink of reactive power for the transmission network, is deployed to provide a reactive power reference from the transmission network for the DN at the transmission-distribution interface.

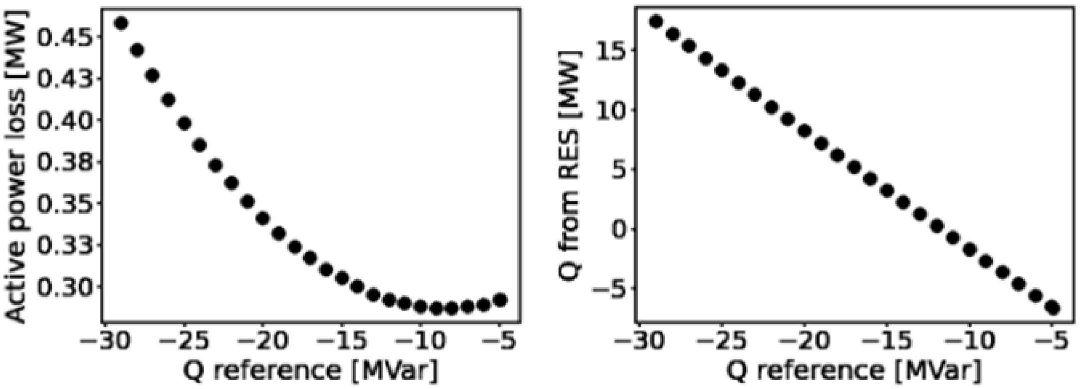
Two scenarios are considered in [16], namely with high and low power generation from the RES, respectively. In the high-power generation from the RES, the DN needs reactive power from the transmission system to sustain the high voltage levels due to high local active power injection. As depicted in Figure 11(a), there is a quadratic relation between reactive power at the transmission-distribution interface and active power losses in case of high-power generation from RES. The optimization sets the RES to inject reactive power in the DN to maintain voltage levels during high generation. However, in Figure 11(b), it is seen that, as the power flow from the transmission to DN is increased, the reactive power injection from the RES is reduced as the reactive power requirement of the DN is now satisfied from the transmission network.



(a) (b)

Figure 11: High generation scenario: a) Active power loss vs. reactive power reference for DSO from TSO; at the transmission -distribution interface; b) reactive power from RES vs. reactive power reference for DSO from TSO [16].

Figure 12 shows that in low power generation scenario, the DN has the potential to supply reactive power to the transmission network. The DN can provide 5.9 MAr up to 30MVar of reactive power to the transmission network. The quadratic relationship between the active power losses and the reactive power at transmission-distribution interface is also depicted in Figure 12(a). In addition, Figure 12(b) portrays the balancing of reactive power from the RES as the reactive power reference at transmission-distribution interface changes.



(a) (b)

Figure 12: Low generation scenario: a) Active power loss vs. reactive power reference for DSO from TSO; at the transmission -distribution interface; b) reactive power from RES vs. reactive power reference for DSO from TSO [16].

4.2.4 Voltage profiles in relation to reactive power

As highlighted in [16], Figure 13 shows that the reactive power flow in the DN might have a direct effect on the voltage profiles and thus on the quality of power supply for the customers.

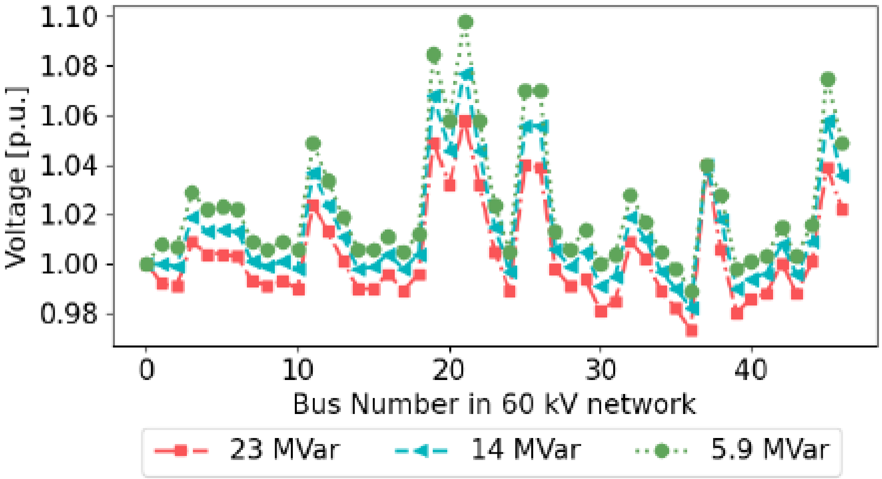


Figure 13: High power generation scenario - voltage profiles at different values of reactive power reference values at the transmission distribution interface [16].

The results show that the voltages at all buses are higher with high local reactive power generation. With a higher local active power generation from the RESs the voltages are closer to the upper voltage limit of 1.1 pu, especially at the buses with RES.

5. Conclusions

Power distribution systems with a high share of Variable Renewable Energy sources (VRE) face problems due to the variability, uncertainty, and non-dispatchable nature of VRE. The substantially increased amount of VRE, such as wind power plants (WPPs) in future distribution networks transforms them into highly weather dependent networks with limited real-time observability. Challenges of such networks, like sustained over-voltage, increased power losses in the network, growing stress upon the existing network assets and changing interactions with the upstream grid. Integrating VRE in distribution networks not only brings challenges to the power system operators but also provides operational, technical and economic opportunities. One of the obvious advantages of connecting power electronic based VRE to the network is, that it provides enhanced control capabilities, which can be utilized to support distribution system operators (DSOs). The power electronics can be thus used as flexible local reactive power sources in the distribution network.

The presented results, validated via simulations on a real distribution network dataset under varying wind and load conditions using actual measurements, demonstrate that WPPs can actively participate in distribution grids to avoid network congestion, maintain supply and reduce the power losses, by locally supplying/ absorbing reactive power. In addition to WPPs, other agents such as tap-changing transformers, capacitor banks can also be controlled, along with WPPs, to further reinforce energy savings. Furthermore, by utilizing the reactive power capability of WPPs, not only reinforces the capability of the existing distribution grid for additional active power flow but also provides the transmission network with required ancillary services for voltage regulation.

Future work can be directed toward deeper investigation and assessment of the potentials of an active transmission-distribution coordination.

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